

Band alignment of epitaxial ZnS/Zn₃P₂ heterojunctions

Jeffrey P. Bosco, Steven B. Demers, Gregory M. Kimball, Nathan S. Lewis, and Harry A. Atwater

Citation: *J. Appl. Phys.* **112**, 093703 (2012); doi: 10.1063/1.4759280

View online: <http://dx.doi.org/10.1063/1.4759280>

View Table of Contents: <http://jap.aip.org/resource/1/JAPIAU/v112/i9>

Published by the [American Institute of Physics](#).

Related Articles

A unique photoemission method to measure semiconductor heterojunction band offsets

Appl. Phys. Lett. **102**, 012101 (2013)

Charge carrier relaxation and effective masses in silicon probed by terahertz spectroscopy

J. Appl. Phys. **112**, 123704 (2012)

Digging up bulk band dispersion buried under a passivation layer

Appl. Phys. Lett. **101**, 242103 (2012)

A combined hard x-ray photoelectron spectroscopy and electrical characterisation study of metal/SiO₂/Si(100) metal-oxide-semiconductor structures

Appl. Phys. Lett. **101**, 241602 (2012)

Determination of the deep donor-like interface state density distribution in metal/Al₂O₃/n-GaN structures from the photocapacitance–light intensity measurement

Appl. Phys. Lett. **101**, 231608 (2012)

Additional information on J. Appl. Phys.

Journal Homepage: <http://jap.aip.org/>

Journal Information: http://jap.aip.org/about/about_the_journal

Top downloads: http://jap.aip.org/features/most_downloaded

Information for Authors: <http://jap.aip.org/authors>

ADVERTISEMENT

The advertisement for AIP Advances features a green and yellow background with a pattern of thin, curved, wavy lines. The AIP Advances logo is prominently displayed in the center, with 'AIP' in blue and 'Advances' in green. To the right of the logo is a circular badge that reads 'Now Indexed in Thomson Reuters Databases'. Below the logo, the text 'Explore AIP's open access journal:' is followed by a list of three bullet points: 'Rapid publication', 'Article-level metrics', and 'Post-publication rating and commenting'.

AIPAdvances

Now Indexed in Thomson Reuters Databases

Explore AIP's open access journal:

- Rapid publication
- Article-level metrics
- Post-publication rating and commenting

Band alignment of epitaxial ZnS/Zn₃P₂ heterojunctions

Jeffrey P. Bosco,^{a)} Steven B. Demers, Gregory M. Kimball, Nathan S. Lewis, and Harry A. Atwater

Watson Laboratory and Noyes Laboratory, Beckman Institute and Kavli Nanoscience Institute, California Institute of Technology, 1200 E. California Blvd., Pasadena, California 91125, USA

(Received 10 September 2012; accepted 25 September 2012; published online 2 November 2012)

The energy-band alignment of epitaxial zb-ZnS(001)/ α -Zn₃P₂(001) heterojunctions has been determined by measurement of shifts in the phosphorus 2*p* and sulfur 2*p* core-level binding energies for various thicknesses (0.6–2.2 nm) of ZnS grown by molecular beam epitaxy on Zn₃P₂. In addition, the position of the valence-band maximum for bulk ZnS and Zn₃P₂ films was estimated using density functional theory calculations of the valence-band density-of-states. The heterojunction was observed to be type I, with a valence-band offset, ΔE_V , of -1.19 ± 0.07 eV, which is significantly different from the type II alignment based on electron affinities that is predicted by Anderson theory. n⁺-ZnS/p-Zn₃P₂ heterojunctions demonstrated open-circuit voltages of >750 mV, indicating passivation of the Zn₃P₂ surface due to the introduction of the ZnS overlayer. Carrier transport across the heterojunction devices was inhibited by the large conduction-band offset, which resulted in short-circuit current densities of <0.1 mA cm⁻² under 1 Sun simulated illumination. Hence, constraints on the current density will likely limit the direct application of the ZnS/Zn₃P₂ heterojunction to photovoltaics, whereas metal-insulator-semiconductor structures that utilize an intrinsic ZnS insulating layer appear promising. © 2012 American Institute of Physics. [<http://dx.doi.org/10.1063/1.4759280>]

Deployment of photovoltaics (PV) on the terawatt scale will require a low-cost, earth abundant, solar absorber with excellent optoelectronic properties. Zinc phosphide (α -Zn₃P₂) has a nearly optimal, direct band gap of 1.50 eV and a high visible-light absorption coefficient ($>10^4$ cm⁻¹) near the band edge.^{1,2} Zn₃P₂ has also been reported to have a long (>5 μ m) minority-carrier diffusion length as well as passive grain boundaries.^{3,4} These properties, in addition to the abundance of elemental zinc and phosphorus, make Zn₃P₂ promising for scalable thin-film photovoltaic applications.

The intrinsically p-type nature of Zn₃P₂ has led to a focus on Mg-Zn₃P₂ “Schottky” type photovoltaic cells, which have been reported to produce solar energy-conversion efficiencies of 6% and 4.3% for bulk and thin film devices, respectively.^{3,5} The efficiency of these devices was limited by absorption and reflection from the Mg metal rectifying contact, by uncontrolled reaction/diffusion of the Mg into the Zn₃P₂ bulk,⁶ and by a resulting high density of trap states at the Zn₃P₂ surface⁷ which caused Fermi-level pinning in the device and hence produced low open-circuit voltages (V_{OC}). Heterojunction devices based on p-Zn₃P₂ absorbers include ZnO, Sn-doped In₂O₃ (ITO), CdS, or ZnSe as n-type emitters.^{8–11} Heterojunction-based Zn₃P₂ devices have however exhibited relatively low V_{OC} ’s, of ≤ 600 mV, and solar energy-conversion efficiencies of $\leq 2\%$. The low V_{OC} values can be attributed to poor band alignment between the emitter and the absorber layers and/or to inadequate interface passivation. Hence, fundamental studies of the band alignment of Zn₃P₂ with n-type semiconductor materials and the resulting impact that the band alignment may

have on carrier transport, surface passivation, and device performance are important to the design of improved Zn₃P₂ heterojunction systems.

Desirable attributes of a heterojunction emitter partner for Zn₃P₂ include an n-type material that has a proper type I band alignment as well as a small conduction-band offset with Zn₃P₂. Zn₃P₂ has a low electron affinity (χ) of 3.6 eV,¹² and thus optimally requires a heterojunction partner that also has a low χ value. ZnS has a reported χ of 3.9 eV (Ref. 13) and is comprised of earth abundant elements. High levels of n-type doping in ZnS ($n > 1 \times 10^{19}$ cm⁻³) have been achieved through non-equilibrium growth techniques that enable the incorporation of extrinsic dopants comprised of either group III or group VII elements.^{14–16} ZnS has also exhibited excellent surface passivation in heterojunctions with other semiconductors, including Si, Cu(In,Ga)Se₂, CdTe, and GaAs.^{17–20} Anderson band alignment theory²¹ predicts a valence-band offset (ΔE_V) and a conduction-band offset (ΔE_C) of roughly -2.5 eV and -0.3 eV, respectively, for a ZnS/Zn₃P₂ heterojunction. However, the actual band offsets often deviate from the ideal values,²² thus highlighting the need for direct measurement of the energy-band alignment.

We report herein the energy-band alignment of zb-ZnS(001)/ α -Zn₃P₂(001) heterojunctions grown by molecular beam epitaxy (MBE). The value of ΔE_V was determined using the method of Kraut *et al.* from high-resolution x-ray photoelectron spectroscopy (XPS) measurements according to²³

$$\Delta E_V = \left(E_{CL}^{ZnS} - E_{VBM}^{ZnS} \right) - \left(E_{CL}^{ZnP} - E_{VBM}^{ZnP} \right) - \Delta E_{CL,i}, \quad (1)$$

where the first two components of Eq. (1) represent the core-level (CL) to valence-band maximum (VBM) energy

^{a)}Author to whom correspondence should be addressed. Electronic mail: jbosco@caltech.edu.

difference measured on the bulk ZnS and Zn₃P₂ surfaces, respectively. In this analysis, the S 2*p* and P 2*p* core-levels were used for ZnS and Zn₃P₂, respectively. $\Delta E_{CL,i}$ represents the energy difference between the S 2*p* and P 2*p* core-levels measured on an ultrathin ZnS/Zn₃P₂ heterojunction interface. From the value of ΔE_V , the corresponding value of ΔE_C was then calculated from the reported values for the band gaps of both of the materials that comprise the heterojunction of interest.

Compound-source epitaxy of Zn₃P₂ and ZnS was performed in an ultrahigh vacuum chamber with an ultimate pressure of $<2 \times 10^{-10}$ Torr.^{16,24} Standard Knudsen effusion cells were used as compound sublimation sources for both Zn₃P₂ and ZnS. Epi-ready, Zn-doped ($>1 \times 10^{18} \text{ cm}^{-3}$), p-type GaAs(001) single crystal wafers (AXT) were used as an epitaxial substrate. GaAs substrates of 1 cm² were mounted with In to a Cu chuck. The substrate was then degassed at 350 °C for 1 h in vacuum. The GaAs native oxide was removed at 450 °C by a ~ 5 min exposure to a RF-generated atomic hydrogen flux.²⁵ Film growths were performed at a substrate temperature of 200 °C. Thick films of Zn₃P₂ and ZnS (>150 nm), denoted as “bulk Zn₃P₂” and “bulk ZnS,” were grown directly on the H-treated GaAs surfaces. The doping levels in the bulk films were $p \sim 1 \times 10^{15} \text{ cm}^{-3}$ and $n \sim 1 \times 10^{17} \text{ cm}^{-3}$ for Zn₃P₂ and ZnS, respectively. A series of ultrathin heterojunctions was fabricated by growth of a thick layer of Zn₃P₂ followed by growth of several monolayers of intrinsic ZnS. These structures are denoted herein by the ZnS film thickness. Hence a 0.6 nm ZnS film grown on Zn₃P₂ is denoted as 0.6 nm ZnS/Zn₃P₂.

XPS data of the P 2*p*, S 2*p*, and valence-band region (including the Zn 3*d* core-level) for each sample were obtained with monochromatic 1486.7 eV x-rays from a Kratos surface science instrument. Photoelectrons were collected at 0° from the surface normal with a detection linewidth of <0.26 eV. All spectra were processed using a “Shirley”-type baseline subtraction.²⁶ The P 2*p* region was fit using two doublet pairs that were modeled as 1:1 Gaussian-Lorentzian product functions. The first doublet represented bulk P–Zn bonding in Zn₃P₂ and the second, weaker doublet represented surface/interface P–P bonding (denoted as P^o). For both doublet pairs, the doublet area ratio was constrained to 2:1, and the doublet separation was constrained to 0.835 eV. The P^o 2*p*^{3/2} peak position was also constrained in the fitting process to 129.30 eV, based on a previous work on P-terminated Zn₃P₂.²⁷ The S 2*p* region was fit using a single doublet that was modeled with 1:1 Gaussian-Lorentzian product functions, with the doublet area ratio and peak separation constrained to 2:1 and 1.20 eV, respectively.

To accurately determine the position of the VBM in the measured spectra for the bulk ZnS and Zn₃P₂ samples, the valence-band region was fit with the valence-band density-of-states (VB-DOS) that was calculated for each material using *ab initio* density functional theory (DFT).²⁸ Calculations were performed within the Kohn-Sham framework and utilized the projector-augmented pseudopotentials as implemented in VASP.²⁹ Valence configurations of 3*d*4*s* were used for Zn and 3*s*3*p* for S and P with the Perdew, Burke, and Ernzerhof (PBE) potential.³⁰ Hybrid density functionals

were also employed, thus addressing the “self-interaction error” and maintaining stronger electron localization. The VB-DOS was convoluted with an instrument-specific spectrometer response function, and was then fit to the leading edge of the valence-band region of the XPS data. The spectrometer response function was determined for the Kratos instrument by measurement of the Au 4*f* doublet, with the spectra fit to a Voigt function assuming an inherent Lorentzian linewidth of 0.317 eV and Gaussian broadening. The details of the convolution and fitting procedure have been outlined previously.³¹

To investigate the effect of the measured band alignment on the performance of heterojunction-based devices, current vs. voltage (*I*-*V*) measurements were performed under dark as well as simulated Air Mass (AM) 1.5 1-Sun illumination conditions on n⁺-ZnS/p-Zn₃P₂ heterojunctions that were grown by molecular-beam epitaxy. The heterojunction was grown on a degenerately doped GaAs substrate ($p > 1 \times 10^{18} \text{ cm}^{-3}$) with a Pt(20 nm)/Ti(30 nm)/Pt(10 nm) back contact. The degenerately doped GaAs was shown to make an ohmic contact to the Zn₃P₂ film. The ZnS and Zn₃P₂ film thicknesses were 120 nm and 1 μm , respectively, with nominal dopant densities of $n = 1 \times 10^{18} \text{ cm}^{-3}$ and $p = 1 \times 10^{15} \text{ cm}^{-3}$, respectively. The total junction area was $\sim 0.35 \text{ cm}^2$, and an Al busbar with fingers was used as a top contact to the ZnS.

Fig. 1 displays reflection high-energy electron diffraction (RHEED) images of (a) a GaAs substrate that had been treated with atomic hydrogen; (b) a thick Zn₃P₂ epilayer surface; (c) a thick ZnS epilayer surface; and (d)–(f) thin ZnS/Zn₃P₂ heterostructures of various thicknesses. All RHEED images were collected with a beam energy of 20 keV that was incident along the GaAs[011] azimuth. The complete removal of the GaAs native oxide was evidenced by a streaky

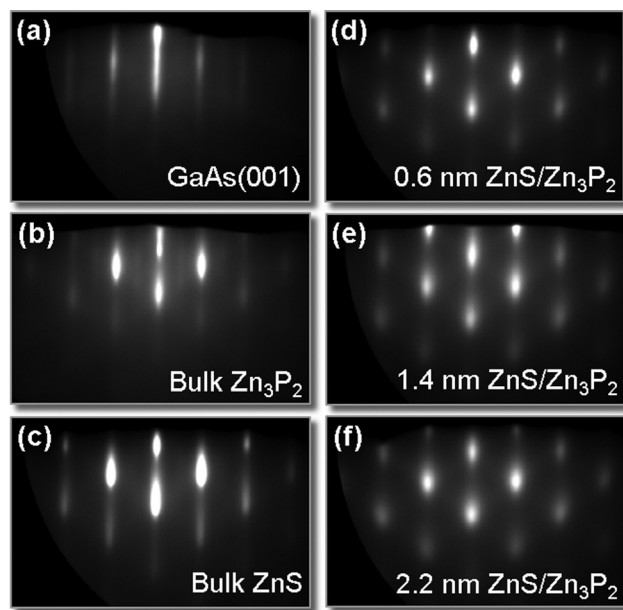


FIG. 1. *In situ* RHEED images of an (a) atomic hydrogen treated GaAs(001) surface, (b) 150 nm bulk Zn₃P₂ film, (c) 150 nm bulk ZnS film, (d) 0.6 nm ZnS/Zn₃P₂, (e) 1.4 nm ZnS/Zn₃P₂, and (f) 2.2 nm ZnS/Zn₃P₂. All RHEED images were obtained using a 20 keV electron beam incident along the [011] direction of the GaAs(001) surface.

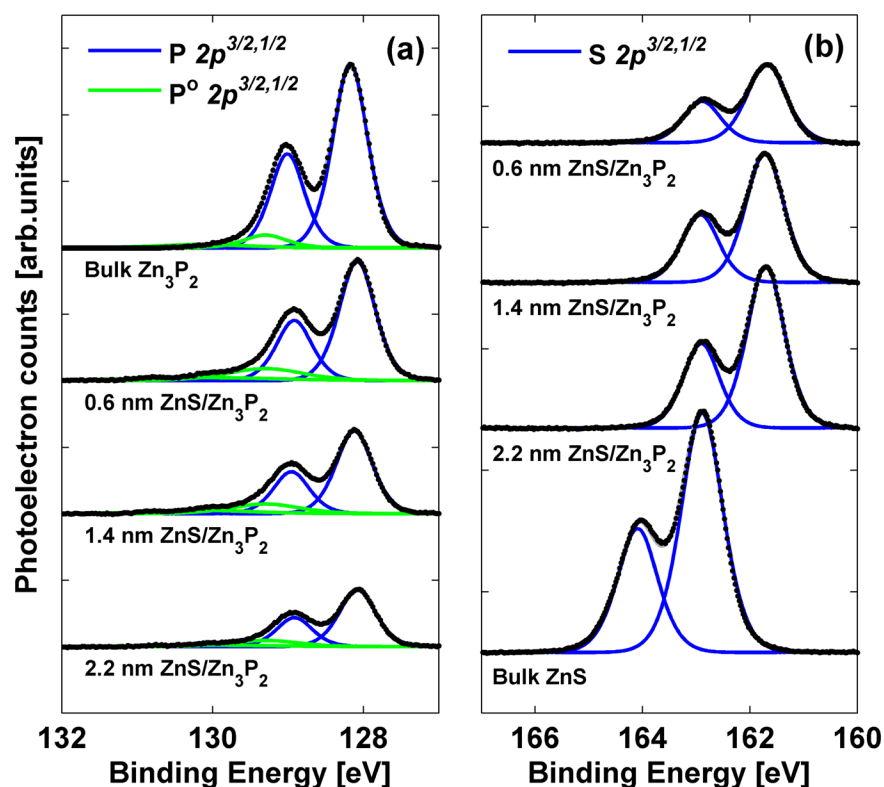


FIG. 2. X-ray photoelectron spectra of (a) P $2p$ and (b) S $2p$ core-levels for bulk Zn_3P_2 , bulk ZnS, and several ultrathin ZnS/ Zn_3P_2 heterojunction interfaces with different ZnS film thickness.

(1×1) surface reconstruction with the faint presence of a fourth-order reconstruction. The Zn_3P_2 grew in the tetragonal (α -phase) crystal structure along the (001) direction with a 45° in-plane rotation with respect to the GaAs lattice, as reported previously.²⁴ The Zn_3P_2 showed a streaky RHEED diffraction pattern, indicating that relatively smooth epitaxial films had been formed. A weak half-order reconstruction was also observed, which can be attributed to a Zn-terminated surface reconstruction. RHEED images of thick ZnS epilayers grown on Zn_3P_2 indicate that the ZnS structure was zinc-blende and that the ZnS grew in the (001) direction. The ultrathin ZnS layers were found to be slightly rougher than the thick layers, as indicated by spotty RHEED images. Relaxation of the ZnS lattice was considered complete upon initiation of growth, with no tetragonal strain observed in the RHEED images.

Fig. 2 displays the XPS data for the P $2p$ and S $2p$ core levels of bulk Zn_3P_2 , bulk ZnS, and the 0.6 nm, 1.4 nm, and 2.2 nm ZnS/ Zn_3P_2 heterojunctions. Oxide species were not observed in any of the core-level spectra. The fitted P $2p^{3/2}$ and S $2p^{3/2}$ core-level binding energies are reported in Table I. The $2p$ core-level position was taken as the mean of the fitted $2p^{3/2}$ and $2p^{1/2}$ peak positions for all of the following calculations. The spectra indicated a shift of ~ 1.2 eV in the S $2p$ binding energy upon formation of the heterojunction interface. However, little or no shift was observed for the P $2p$ binding energy. The core-level binding energy differences ($\Delta E_{\text{CL},i}$) observed for all interface samples are displayed in Table I. An average value of $\Delta E_{\text{CL},i} = 33.78 \pm 0.03$ eV was calculated for the five heterojunction samples.

Fig. 3 displays the XPS data obtained for the valence-band region of (a) bulk Zn_3P_2 , (b) bulk ZnS, and (c) the

TABLE I. A complete list of P $2p^{3/2}$ and S $2p^{3/2}$ binding energies for all samples studied. Calculated $E_{\text{CL}} - E_{\text{VBM}}$ for bulk samples and $\Delta E_{\text{CL},i}$ and ΔE_{V} for heterojunction samples are also included. All values are reported in eV.

| Sample | P $2p^{3/2}$ | S $2p^{3/2}$ | $\Delta E_{\text{CL},i}$ | $E_{\text{CL}} - E_{\text{VBM}}$ | ΔE_{V} | |
|-------------------------------------|--------------|--------------|--------------------------|----------------------------------|-----------------------|---------------------|
| | | | | | Kraut ^a | Direct ^b |
| Bulk Zn_3P_2 | 128.17(4) | ... | ... | 128.46(9) | ... | ... |
| Bulk Zn_3P_2 | 128.13(6) | ... | ... | 128.51(5) | ... | ... |
| 0.6 nm ZnS/ Zn_3P_2 | 128.08(2) | 161.69(2) | 33.79(2) | ... | -1.20 | -1.01 |
| 1.0 nm ZnS/ Zn_3P_2 | 128.20(1) | 161.79(3) | 33.77(5) | ... | -1.19 | -1.15 |
| 1.4 nm ZnS/ Zn_3P_2 | 128.12(0) | 161.72(3) | 33.78(5) | ... | -1.20 | -1.12 |
| 1.8 nm ZnS/ Zn_3P_2 | 128.20(8) | 161.76(2) | 33.73(6) | ... | -1.15 | -1.18 |
| 2.2 nm ZnS/ Zn_3P_2 | 128.07(9) | 161.70(6) | 33.80(9) | ... | -1.22 | -1.15 |
| Bulk ZnS | ... | 162.89(1) | ... | 161.07(1) | ... | ... |
| Bulk ZnS | ... | 162.75(7) | ... | 161.08(7) | ... | ... |

^aValence-band offset as calculated by the Kraut method using Eq. (1).

^bValence-band offset as determined by direct fitting of the interface valence-band spectra as a superposition of the bulk valence-band spectra.

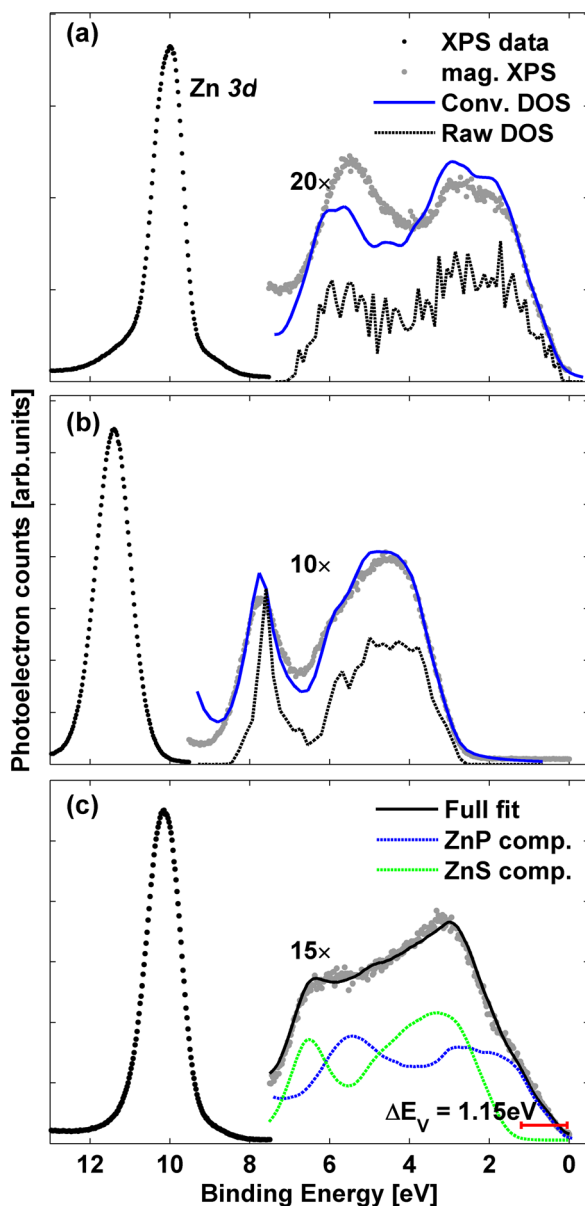


FIG. 3. XPS data of the valence-band region for (a) bulk Zn₃P₂, (b) bulk ZnS, and (c) a 1 nm ZnS/Zn₃P₂ heterojunction interface. For bulk samples, the raw and convoluted VB-DOS calculations that were used for determining the VBM are displayed. For the interface sample, the valence-band region was fit using a superposition of the bulk ZnS and bulk Zn₃P₂ valence-band spectra.

1.0 nm ZnS/Zn₃P₂ interface. For the bulk samples, the VB-DOS is also displayed as calculated (Raw DOS) as well as after convolution with the spectrometer response function (Conv. DOS). Excellent agreement was observed between the shape of the convoluted VB-DOS and the valence-band data collected by XPS. A ~ 0.24 eV difference was observed in the position of the ZnS VBM determined by the VB-DOS fitting relative to the value obtained using conventional linear extrapolation of the valence-band leading edge. The difference was likely due to a low calculated DOS near the edge of the valence-band. The low DOS was captured by the tail of the leading edge of the XPS spectra, which is not well represented by the linear extrapolation method, thus resulting in an overestimation of the VBM position. The core-level to

VBM energy difference ($E_{\text{CL}} - E_{\text{VBM}}$) for bulk samples as determined by the VB-DOS fitting is listed in Table I. Average values for $E_{\text{CL}} - E_{\text{VBM}}$ of 128.49 ± 0.03 eV and 161.08 ± 0.01 eV were obtained for the bulk Zn₃P₂ and bulk ZnS samples, respectively.

From the core-level binding energies and VBM positions determined using the VB-DOS fitting, Eq. (1) yielded $\Delta E_{\text{V}} = -1.19 \pm 0.07$ eV. The ΔE_{V} was found to be independent of ZnS film thickness (see Table I), indicating minimal contributions due to any band bending near the interface. A direct determination of ΔE_{V} was also performed by fitting the measured valence-band spectra of a heterojunction interface to a superposition of the valence spectra of bulk ZnS and Zn₃P₂.²² As displayed in Fig. 3(c) for the 1 nm ZnS/Zn₃P₂ sample, this process yielded excellent agreement between the fit and the XPS data. A value of ΔE_{V} was then directly calculated from the difference in the VBM positions of the superimposed bulk spectra. The fitted ΔE_{V} was similar across all heterojunction samples (see Table I) and resulted in an average $\Delta E_{\text{V}} = -1.12 \pm 0.07$ eV, which is consistent with the value of ΔE_{V} determined from Eq. (1). Use of the known band gaps for ZnS and Zn₃P₂ of 3.68 eV and 1.51 eV, respectively, yielded $\Delta E_{\text{C}} = 0.98 \pm 0.07$ eV.

The observed band alignment for the ZnS/Zn₃P₂ heterojunction interface differs significantly from the alignment predicted by Anderson theory (type I versus type II). Unlike devices comprised of III-V and II-VI compound semiconductors, the interfacial dipole that is expected to occur for the mixed II-VI/II-V heterojunction is currently not well elucidated. Ruan and Ching³² proposed a simple theory for predicting deviations from Anderson theory based on interfacial dipole formation in the absence of interface defects. Their model predicts a decrease in the ΔE_{V} due to charge transfer from the higher valence-band material (in this case Zn₃P₂) to the lower valence-band material. Using their model, a ΔE_{V} between ZnS and Zn₃P₂ of -1.1 ± 0.1 eV is calculated, which is in excellent quantitative agreement with the experimentally measured offset.³⁴

The measured electronic structure of the ZnS/Zn₃P₂ heterojunction may reflect effects of interfacial crystalline strain as well as interfacial chemical reactions. The *in situ* RHEED data indicated that the ZnS layers relaxed immediately upon film growth (see Fig. 1), implying that interfacial strain effects are minimal. Interfacial strain should also produce band offsets that depended on the thickness of the overlayer, in contrast to the experimental observations. Interfacial chemical reactions between P and S could produce deviations in the band alignment. Consistently, P-P bonding, or possibly P-S bonding, was observed in the XPS measurements of the ultrathin heterostructure samples. Attempts to limit reactions by exposing the Zn₃P₂ surface to a Zn metal flux immediately prior to ZnS deposition had no detectable effect on the XPS measurements or on the observed band alignment.

Fig. 4 displays the calculated band alignment of the proposed n⁺-ZnS/p-Zn₃P₂ heterojunction under equilibrium conditions. The energy-bands were simulated using the AFORS-HET³³ device modeling software package, assuming $\Delta E_{\text{V}} = -1.19$ eV and realistic doping levels of

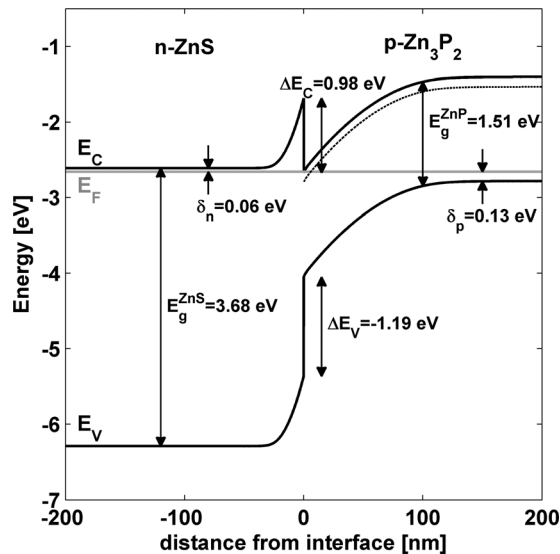


FIG. 4. The energy-band alignment for a ZnS/Zn₃P₂ heterojunction interface that was calculated given the experimentally measured ΔE_V and given the assumed doping levels of $n = 1 \times 10^{18} \text{ cm}^{-3}$ and $p = 1 \times 10^{17} \text{ cm}^{-3}$ for ZnS and Zn₃P₂, respectively. The dotted line below the conduction-band of Zn₃P₂ represents the indirect band gap of 1.38 eV.²

$n = 1 \times 10^{18} \text{ cm}^{-3}$ and $p = 1 \times 10^{17} \text{ cm}^{-3}$ for the ZnS and Zn₃P₂, respectively. The simulations demonstrated the existence of a large conduction-band spike at the ZnS/Zn₃P₂ interface due to the measured band offset. The conduction-band spike was found to inhibit charge transfer at the heterojunction interface and indicates that ZnS is a non-optimal emitter layer for Zn₃P₂. I-V measurements performed on n⁺-ZnS/p-Zn₃P₂ heterojunctions confirmed this notion (Fig. 5), exhibiting short-circuit current densities of $<0.1 \text{ mA cm}^{-2}$ under simulated AM1.5 1-Sun illumination. However, the devices consistently demonstrated V_{OC} 's of $>750 \text{ mV}$, indicating improved interface passivation over previously fabricated heterojunctions implementing Zn₃P₂ as an absorber layer. These results suggest that ZnS can provide a good surface passivation layer for Zn₃P₂ and may be useful as a thin, intrinsic layer in metal-insulator-semiconductor (MIS) or

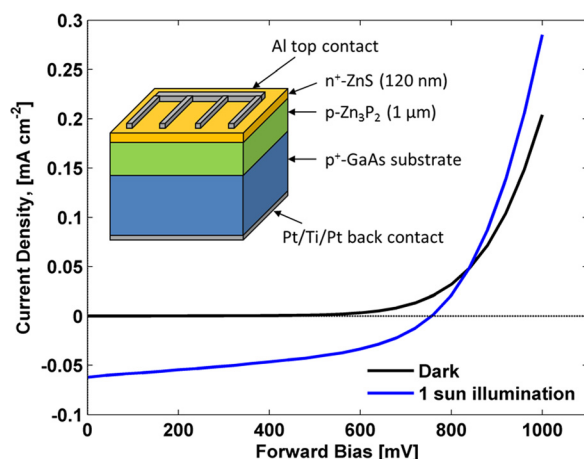


FIG. 5. I-V measurements for an MBE grown n⁺-ZnS/p-Zn₃P₂/p⁺-GaAs heterojunction device under dark and AM1.5 1-Sun illumination conditions. A schematic of the device is shown in the inset.

semiconductor-insulator-semiconductor (SIS) photovoltaic devices.

ACKNOWLEDGMENTS

This work was supported by the Dow Chemical Company and by the Department of Energy, Office of Basic Energy Sciences under Grant No. DE-FG02-03ER15483. The authors would like to thank Joseph Beardslee for his assistance with the Kratos XPS measurements. J.P.B. acknowledges the NSF for a graduate research fellowship.

- ¹J. M. Pawlikowski, *Phys. Rev. B* **26**, 4711 (1982).
- ²G. M. Kimball, A. M. Müller, N. S. Lewis, and H. A. Atwater, *Appl. Phys. Lett.* **95**, 112103 (2009).
- ³M. Bhushan and A. Catalano, *Appl. Phys. Lett.* **38**, 39 (1981).
- ⁴K. W. Mitchell, *Annu. Rev. Mater. Sci.* **12**, 401 (1982).
- ⁵M. Bhushan, *Appl. Phys. Lett.* **40**, 51 (1982).
- ⁶L. L. Kazmerski, P. J. Ireland, and A. Catalano, *J. Vac. Sci. Technol.* **18**, 368 (1981).
- ⁷M. S. Casey, A. L. Fahrenbruch, and R. H. Bube, *J. Appl. Phys.* **61**, 2941 (1987).
- ⁸P. S. Nayar and A. Catalano, *Appl. Phys. Lett.* **39**, 105 (1981).
- ⁹T. Suda, M. Suzuki, and S. Kurita, *Jpn. J. Appl. Phys., Part 2* **22**, L656 (1983).
- ¹⁰T. Suda, A. Kuroyanagi, and S. Kurita, in *Technical Digest, International PVSEC-1, Kobe, Japan* (PVSEC, Tokyo, 1984), p. 381.
- ¹¹K. Kakishita, K. Aihara, and T. Suda, *Sol. Energy Mater. Sol. Cells* **35**, 333 (1994).
- ¹²A. J. Nelson, L. L. Kazmerski, M. Engelhardt, and H. Hochst, *J. Appl. Phys.* **67**, 1393 (1990).
- ¹³R. K. Swank, *Phys. Rev.* **153**, 844 (1967).
- ¹⁴M. Kitagawa, Y. Tomomura, A. Suzuki, and S. Nakajima, *J. Cryst. Growth* **95**, 509 (1989).
- ¹⁵S. Yamaga, A. Yoshikawa, and H. Kasai, *J. Cryst. Growth* **106**, 683 (1990).
- ¹⁶J. P. Bosco, S. F. Tajdar, and H. A. Atwater, "Molecular beam epitaxy of n-type ZnS: A wide-bandgap emitter for heterojunction PV devices," *Proc. 18th IEEE Photovol. Spec. Conf.*, Austin, June 3-8 2012 (IEEE, New York, 2012).
- ¹⁷G. A. Landis, J. J. Loferski, R. Beaulieu, P. A. Sekulamoise, S. M. Vernon, M. B. Spitzer, and C. J. Keavney, *IEEE Trans. Electron Devices* **37**, 372 (1990).
- ¹⁸Y. H. Kim, S. Y. An, J. Y. Lee, I. Kim, K. N. Oh, S. U. Kim, M. J. Park, and T. S. Lee, *J. Appl. Phys.* **85**, 7370 (1999).
- ¹⁹T. Nakada, M. Mizutani, Y. Hagiwara, and A. Kunioka, *Sol. Energy Mater. Sol. Cells* **67**, 255 (2001).
- ²⁰J. M. Woodall, G. D. Pettit, T. Chappell, and H. J. Hovel, *J. Vac. Sci. Technol.* **16**, 1389 (1979).
- ²¹R. L. Anderson, *Solid-State Electron.* **5**, 341 (1962).
- ²²A. Franciosi and C. G. VandeWalle, *Surf. Sci. Rep.* **25**, 1 (1996).
- ²³E. A. Kraut, R. W. Grant, J. R. Waldrop, and S. P. Kowalczyk, *Phys. Rev. Lett.* **44**, 1620 (1980).
- ²⁴J. P. Bosco, G. M. Kimball, N. S. Lewis, and H. A. Atwater, "Pseudomorphic growth and strain relaxation of α -Zn₃P₂ on GaAs(001) by molecular beam epitaxy," *J. Cryst. Growth* (unpublished).
- ²⁵A. Khatiri, J. M. Ripalda, T. J. Krzyzewski, G. R. Bell, C. F. McConville, and T. S. Jones, *Surf. Sci.* **548**, L1 (2004).
- ²⁶D. A. Shirley, *Phys. Rev. B* **5**, 4709 (1972).
- ²⁷G. M. Kimball, J. P. Bosco, A. M. Müller, S. F. Tajdar, B. S. Brunschwig, H. A. Atwater, and N. S. Lewis "Passivation of Zn₃P₂ substrates by aqueous chemical etching and air oxidation," *J. Appl. Phys.* (Communication) (to be published).
- ²⁸S. Demers and A. van de Walle, *Phys. Rev. B* **85**, 195208 (2012).
- ²⁹G. Kresse and J. Furthmüller, *Comput. Mater. Sci.* **6**, 15 (1996).
- ³⁰J. P. Perdew, K. Burke, and M. Ernzerhof, *Phys. Rev. Lett.* **77**, 3865 (1996).
- ³¹E. A. Kraut, R. W. Grant, J. R. Waldrop, and S. P. Kowalczyk, *Phys. Rev. B* **28**, 1965 (1983).
- ³²Y.-C. Ruan and W. Y. Ching, *J. Appl. Phys.* **62**, 2885 (1987).

³³R. Stangl, M. Kriegel, S. Kirste, M. Schmidt, and W. Fuhs, in Proceedings of the IEEE Photovoltaic Specialists Conference, Orlando, FL, USA, 2005.

³⁴See supplementary material at <http://dx.doi.org/10.1063/1.4759280> for supplementary material includes: (1) XPS survey spectra for bulk and

heterojunction samples; (2) the instrument response function fitting of the Au 4f core-level; (3) plots of the direct determination of the valence-band offset for all heterojunction samples; and (4) a detailed example of the valence-band offset calculation proposed by Ruan and Ching applied to the ZnS/Zn₃P₂ heterojunction.